SESM3032 Coursework

Heat Conduction Modelling and Optimisation with COMSOL™

Objectives

- Apply FEM modelling workflow to build and solve COMSOL models for heat conduction problems of complex geometries.
- Use symmetry where appropriate for model simplification and faster computation
- Extract, present, and interpret modelling results for analysis, discussion, and comparison with analytical results given in lectures
- Optimise fin and heat-sink designs to meet given specifications and outline strategies to manage operations above the nominal heat load

Report

- The coursework text should be written as lab report rather than an essay. It should include a short introduction at the beginning and conclusions at the end. The report should cover all of the modelling tasks A1-A9 and B1-B7 detailed below
- COMSOL models used should be presented in sufficient details to include the geometries, material properties, boundary conditions, meshing
- Justifications for the choices of material, heat transfer, and geometric parameters should be included and used for qualitative estimate where possible
- The methods/formulae for derived quantities, such as total heat transferred Q, fin effectiveness ϵ_f, and fin efficiency η_f, should be given in terms of functions/operations of modelling results
- Discussions and comments on the modelling results are essential. A collection of graphs/figures without explanation/interpretation is insufficient
- No limit on words count or length

Coursework Part A: Radial Fin Modelling and Optimisation (40%)

Use COMSOL to model a radial fin with a rectangular profile area $A_p = (r_2 - r_1)d$ where d is the fin thickness, r_1 the inner radius at the fin root, and r_2 the outer radius at the fin tip. The fin operates at root temperature T_b for heat transfer by convection with an environment at temperature T_∞. The tube itself does not have to be a part of the model when T_b is set on the tube's outer surface. Carry out the following modelling tasks:

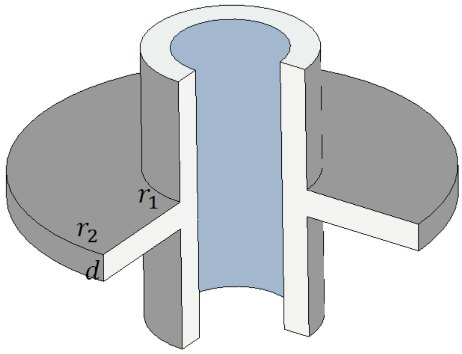

Figure 1: Radial fin illustration

- Build COMSOL Model
  - A1 Use appropriate dimensionality and symmetry to create a flat radial fin that has fixed temperature T_b at the root and is cooled down by convection with an environment at surrounding temperature T_∞. Define the following parameters: root temperature T_b, fluid temperature T_∞, convective heat transfer coefficient h, fin thermal conductivity k, fin profile area A_p, fin inner and outer radius r_1 and r_2 respectively, and fin thickness d. Justify the values chosen for the parameters and make sure T_b and T_∞ are sufficiently different for a meaningful heat transfer.
- Solution and Analysis
  - A2 Calculate the steady state solution for the values assigned above to the parameters. Plot the fin temperature profile along the radial direction. For comparison in the same graph, also plot the analytical temperature profile of a plate fin of the same thickness and length. Comments on their similarities and differences and offer your explanations.
  - A3 Use the solution to calculate the fin heat transferred Q_f, fin effectiveness ϵ_f, and fin efficiency η_f; compare the values with those of obtained with the radial fin efficiency chart $\eta_f(F_p)$ provided in the handout (slides 93-94).
  - A4 Comment on the performance of your initial fin design and discuss the scopes for enhancement or downscaling. Adjust the geometric design and material selection until, in your judgement, the results are satisfactory and representative for an effective fin.
- Optimisation
  - A5 Model by parametric sweep to obtain and plot the fin heat transfer Q_f as a function of the fin thickness d, which is swept while the fin length varies accordingly with the inner radius r_1 and the profile area A_p remain constant as initially assigned. Calculate and plot the corresponding fin efficiency η_f as a function of d. Find the optimal fin thickness d_{opt} and the corresponding optimal fin length for the maximum Q_f. Comments on the practicality and manufacturability of the optimal fin geometry.
  - A6 Model by parametric sweep to obtain and plot η_f as a function of the fin parameter F_p. Use the fin thickness d as the sweeping parameter while for the fin length varies accordingly with maintaining $(r_2 + d/2) = 2r_1$ and A_p constant. Compare the results with that provided in the handout (slides 93-94) for flat radial fins. Repeat the sweep for $(r_2 + d/2) = 1.5r_1$ and $(r_2 + d/2) = 3r_1$ for further comparison.
- Radial Fin Array
  - A7 Build a simple heat exchanger model of an array of 11 radial fins evenly spaced along a length of tube of the same material as the fins. Assign a sensible tube thickness relative to r_1 and define the tube length as an additional parameter.
  - A8 Model the heat exchanger for condensing saturate steam at 1atm insider the tube by cooling air at $T_\infty = 20°\text{C}$ flowing outside over the fin and the tube with same heat transfer coefficient h used for the fin optimisation at the assigned profile area A_p.

A9 Calculate and plot the temperature distribution along the tube and fin for the optimal fin design and 3 different tube lengths. Discuss the characteristics of the temperature profile and explain the changes according to the tube length. Calculate the corresponding water condensation rates achieved.

Coursework Part B: Design and Modelling a Pin-fin Array Heat-sink for CPU Cooling (60%)

With the increasing level of integrations in modern electronics, their power consumption per components has been also increasing. State-of-the-art CPUs have heat flux in excess of heat flux of 100Wcm^{-2}. A typical heat-sink with pin-fin arrays for CPU cooling consists of a collection of pin-fins attached at root to a flat copper disc which is known as the heat spreader for direct contact with the CPU chip (see figure on the right). Complete the following design and modelling tasks:

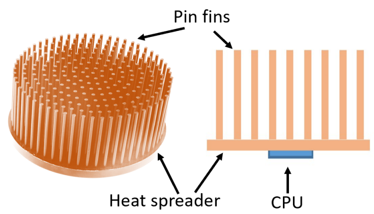

Figure 2: A pin-fin array heat-sink

B1 Use Newton's law of cooling to determine the required heat transfer coefficient by air at $T_\infty = 20^o$C for direct convection cooling of the chip area of 3.5mm radius for a CPU heat loads maximum of 50W at maximum CPU temperature of $T_S = 70^o$C. Calculate the CPU temperatures at lower heat loads of 0.5W and 5W. Repeat the calculations for a round heat spreader of a radius 30mm. Explain why results justify the need for a heat-sink with further extended surfaces.

B2 Use COMSOL (similar to A5 above) to obtain the optimal cylindrical pin-fin design (radius and length) for a fixed fin volume V_f, fin thermal conductivity k, and a *realistic* heat transfer coefficient h for natural convection by air. Justify the choices for fin material, fin volume $50 \leq V_f \leq 200\,\text{mm}^3$, and air heat transfer coefficient h. Plot Q_f as a function of fin radius to show the optimal heat transfer obtained for a root temperature $T_v = 65^o$C and air temperature $T_\infty = 20^o$C. Estimate the number of pin-fins required for the pin-fin array heat-sink for a maximum CPU heat lead of 50W.

B3 Build a 3D model to include the round heat spreader and with an array of your optimal cylindrical pin-fins distributed in pattern of your choice. The heat spreader should have a radius $R \leq 30$mm and have an appropriate thickness δ. The exposed lower surface of the spreader is considered adiabatic except for a boundary condition of given heat flux $q = Q/A_{\text{CPU}}$ where the spreader is attached to the CPU die. The spreader upper surface and the fin surfaces should be subjected to a convective boundary condition with the heat transfer coefficient h given in B2 and the ambient at $T_\infty = 20^o$C. It's important to use symmetry of pin-fin distribution and appropriate meshing to ensure a manageable COMSOL model for your PC.

B4 Obtain steady state solutions for your design for several heat loads levels of $Q \in [0.5, 50]$ W. Identify and explain location for the maximum temperature $T_{\max}$, then plot $T_{\max}$ as a function of Q. Adjust the spreader thickness δ for sufficient robustness and a good compromise between the thermal resistances along and across the spreader.

B5 For a $T_{\max}$ significantly above or below 70^oC, increase or decrease the number of pin-fins accordingly. In case of a very high $T_{\max}$, consider if the heat transfer coefficient might be increased with justification.

B6 For the $Q = 50$W, obtained the transient behaviour of the heat-sink desgin finalised in B5. with the geometry found in B5 and an initial condition of $T_i = 20^o$C. Determine the time required for $T_{\max}$ to reach 68^oC.

B7 Model the transient behaviour at a higher heat load, e.g., an overclocked CPU with $Q = 65$W and explain how to used the result for devising a throttling scheme for a minimal impact on the computation speed. Propose a dynamic heat load profile to sustain the CPU performance as high as possible. Solve the transient problem with the proposed dynamic load profile instead of a constant heat load.